

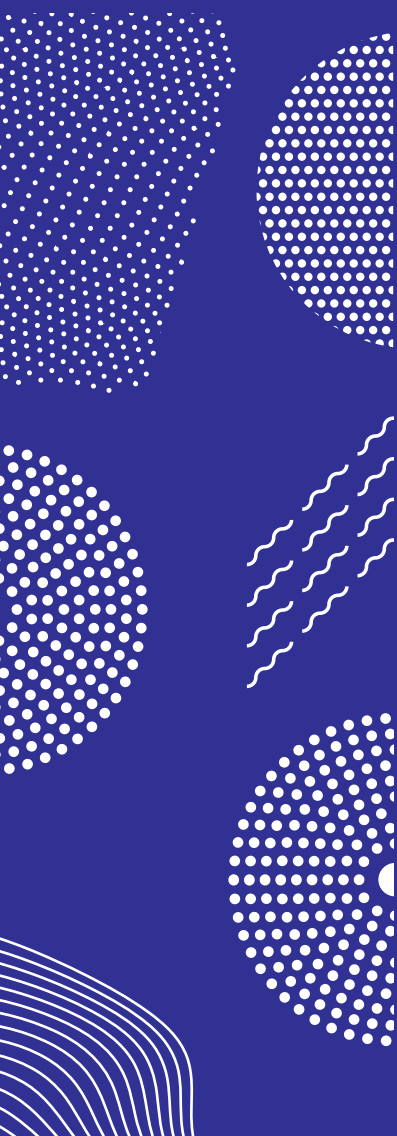


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# REVIEW ON WINDS, EXTRATROPICAL CYCLONES AND THEIR IMPACTS IN NORTHERN EUROPE AND FINLAND

HILPPA GREGOW  
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# **Review on winds, extratropical cyclones and their impacts in Northern Europe and Finland**

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Review on winds, extratropical cyclones and their impacts in Northern Europe and Finland

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#### Abstract

Strong winds caused by powerful extratropical cyclones are one of the most dangerous and damaging weather phenomena in Northern Europe. Stormy winds can generate extreme waves and rise the sea level, which leads occasionally to storm surges in coastal areas. In land areas, strong winds can cause extensive forest damage. In general, windstorms induce annually significant damage for society. Moreover, due to climate change, the frequency and the impacts caused by the windstorms is changing.

In this report, we introduce a literature review on the occurrence of strong winds, extratropical cyclones and their impacts in Northern Europe. We present the most important findings on both past trends and current climate on wind speeds and extratropical cyclones based on in-situ measurements and reanalysis data. We also briefly analyse impacts caused by extreme convective weather. Furthermore, we aim to respond to the question on how the wind climate in Northern Europe is going to change in the future under climate change.

The decadal changes in the frequency of extratropical cyclones in Northern Europe follows the changes in the storm track regions. Regarding the past climate, confident estimates of the past trends are difficult to make due to inhomogeneities in the number and type of assimilated wind speeds into reanalysis data. Based on homogenized in-situ observations, the wind climatology in 1959-2015 in Finland shows a slight downward trend, but no trend is evident in the number of potential forest damage days in Finland. Possible change points are however detected for wind speeds and the impacts. Forest damage is not only a function of wind speeds but also the environmental factors, such as the amount of frost in the ground, play a role.

In the future, the strongest signal in Northern Europe for slightly increasing wind speeds is in the autumn while other seasons do not show remarkable trends. It has been shown that the total number of the strongest windstorms are projected to decrease in the North Atlantic and Europe, but regional differences are likely to appear due to changes in the storm tracks. The strong wind gusts associated with thunderstorms in parts of Northern Europe will likely increase in frequency by the end of the 21st century.

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Tiivistelmä

Voimakkaista keskileveysasteiden matalapaineista johtuvat myrskytuulet ovat yksi eniten vaaraa ja vahinkoa aiheuttavista sääilmiöistä Pohjois-Euroopassa. Myrskytuulet aiheuttavat korkeita aaltoja ja nostavat meriveden pintaa, mikä johtaa toisinaan merivesitulviin. Sisämaassa voimakkaat myrskytuulet aiheuttavat ajoittain laajoja metsätuhoja. Myrskyistä koituu vuosittain merkittäviä vahinkoja yhteiskunnalle. Ilmastomuutoksen myötä myrskyjen toistuvuus ja tuulista johtuvat tuhot muuttuvat.

Raportissa käydään kirjallisuuden pohjalta läpi voimakkaiden tuulien ja myrskyjen esiintyvyyttä Pohjois-Euroopassa. Raportissa esitellään tärkeimmät havaintoihin ja uusanalyysihin perustuvat tutkimustulokset tuulista, myrskyistä ja niiden vaikutuksista. Lisäksi esitellään lyhyesti muutoksia konvektiivisten säähäiriöiden aiheuttamissa tuulissa. Lopuksi pyritään vastaamaan kysymykseen, miten tuulisuus tulee muuttumaan Pohjois-Euroopassa ilmastomuutoksen myötä.

Myrskyjen lukumäärän alueelliset muutokset ovat sidoksissa myrskyratojen muutoksiin. Menneiden myrskytrendien tutkiminen uusanalyysien avulla on kuitenkin osoittautunut ongelmalliseksi, koska eri uusanalyysihin on assimiloitu vaihteleva määrä ilmakehän havaintoja ja siten aineisto on epähomogeenista. Yksittäisten uusanalyysien pohjalta ei näin ollen voida tehdä varmoja johtopäätöksiä menneistä myrskytrendeistä. Kirjallisuuden mukaan voimakkaat tuulet ovat olleet Suomessa laskusuunnassa vuosina 1959-2015, mutta potentiaaliset metsätuhopäivät Suomessa eivät näytä vähentyneen. Metsätuhojen määrään vaikuttaa tuulisuuden lisäksi myös muun muassa maaperän roudan määrä. Metsätuhojen ja tuulisuuden trendeissä on lisäksi havaittu viime vuosina mahdollisia käännekohtia.

Tutkimusten mukaan Pohjois-Euroopassa ei ole odotettavissa suurta muutosta tuulisuudessa, joskin syksyisin keskimääräisen tuulisuuden odotetaan hieman lisääntyvän. Voimakkaiden myrskyjen kokonaislukumäärä Pohjois-Atlantilla tulee todennäköisesti laskemaan, mutta alueellisia eroja voi ilmetä myrskyratojen muutoksista johtuen. Kesän rajuilmoihiin liittyviä voimakkaita tuulenpuuskuja voi vuosisadan loppuun mennessä Pohjois-Euroopassa esiintyä useammin kuin nykyilmastossa.

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## Foreword

This report originates from a project deliverable report D1.3.2 “Review on strong winds and storms in Northern Europe in the past, current and future climate” that was created in SAFIR2018 EXWE project in 2017. The deliverable D1.3.2 was originally thought to be published after the final acceptance of the cited research articles that were then still under the review process. Some of these research articles went through major revisions several times and the waiting continued. At the same time new projects related to winds and storms were starting and more research results were expected to become available. In the beginning of 2020, the research was mature enough with respect to wind and storm research in Finland. Thus, we revisited the old deliverable report and analysed what could be done. Much could be. With the help of our reviewers, our storyline changed even more.

This report is now reviewing not only literature on winds and storms but also on impacts. In the Appendix the strongest windstorms and convective storms with significant impacts are listed. In the beginning we describe the main terminology used, as there are many ways to express concepts that deal with extremes and storms. We also discuss what the gaps are in managing windstorm and climate change induced risks in Northern Europe with a specific focus on Finland. With respect to thunderstorm detection also machine learning opportunities are briefly described.

This report in its current form summarises research results relevant to European Research Area for Climate Services (ERA4CS) WINDSURFER project and national projects MONITUHO and SUOMI which are mentioned in the acknowledgments. We hope that by reading this report, the reader is updated with the latest knowledge related to winds, storms and their impacts in Northern Europe in the past, current and future climate.

In Helsinki 20.8.2020

Hilppa Gregow

Adj.Prof. in Meteorology and Climatic Risks

Head of Unit, Weather and Climate Change Impact Research

## List of concepts

### *Decadal average, seasonal average*

Wind speeds averaged over different time periods. Decadal average is wind speed averaged over a decade, and seasonal average means an average over a season. These can be used together, for example decadal winter average means an average over 10-year period using only observations from Dec-Jan-Feb period.

### *Extratropical cyclone (ETC)*

Large-scale weather system ranging in size from several hundreds to few thousand kilometers. ETCs cause precipitation and winds and are responsible for the daily weather variation in mid-latitudes. Powerful ETCs (see *windstorm*) can cause large damage for society and forestry due to their strong winds.

### *Gridded data*

Data format in which in-situ observations are interpolated into a spatial grid. The value in each grid cell corresponds to the conditions averaged over the grid cell area, and thus a single point value inside the grid cell can be considerably higher (or lower).

### *Hurricane*

A tropical cyclone with sustained winds higher or equal to  $33 \text{ ms}^{-1}$  occurring in the North Atlantic or Eastern North Pacific.

### *Reanalysis*

Consistent description of atmospheric state in which all available observations and the atmospheric model analysis have been combined in a scientific method, for over several decades or longer. Reanalyses typically cover the entire globe from the Earth's surface to the stratosphere. They are useful for monitoring changes in climate conditions and therefore used extensively in atmospheric research.

### *Return period*

Expected time between events of similar intensity. It is an inverse of probability; for example, the return period of wind speed exceeding  $30 \text{ m s}^{-1}$  might be 100 years, so its annual probability of occurrence in any given year is 1/100 or 1 %.

### *Storm track*

A region which is characterized by a high ETC activity. In other words, an area or track where ETCs tend to travel.

### *Wind observation*

Observed wind speed based on in-situ measurements. Wind observations are done typically at 10 meter altitude and the speed is averaged over 10 minutes.

### *Windstorm*

A powerful ETC marked with very strong winds. No universal and objective definition exists. In Finland, ETCs with average wind speed equal to or higher than  $21 \text{ ms}^{-1}$  are classified as storms.

### *98th percentile of wind speed*

A wind speed which falls into the highest 2 % of all measurements.

## **Contents**

<b>Introduction</b>	<b>7</b>
<b>Past and current climate</b>	<b>8</b>
2.1 Wind speeds	8
2.1.1 Trends in wind speeds based on observations	8
2.1.2 Wind speeds based on reanalyses	11
2.2 Extratropical cyclones	12
2.2.1 Extratropical cyclones based on reanalyses and in-situ observations	12
2.2.2 Extratropical cyclones based on observed impacts	14
2.3 Strong winds induced by extreme convective weather	17
<b>Future conditions</b>	<b>20</b>
3.1 Wind speeds	20
3.2 Extratropical cyclones	24
3.3 Strong winds induced by extreme convective weather	26
<b>Concluding remarks</b>	<b>27</b>
<b>Acknowledgements</b>	<b>29</b>
<b>References</b>	<b>29</b>
<b>Appendix</b>	<b>34</b>

## 1. Introduction

Northern Europe is a loosely defined geographical region covering parts of the North Atlantic and the European continent, and Finland is located in its northeastern part. The strongest wind speeds in Northern Europe are associated with the passage of extratropical cyclones (hereafter ETCs) moving from the North Atlantic along the so-called storm track region (Wernli and Schwerz, 2006) towards east or northeast. In this report, we focus our review on winds, ETCs and their impacts in Northern Europe. Some more details are given for Finland, and in terms of ETCs, also for the North Atlantic which is the main development region for ETCs affecting Finland.

ETCs are responsible for most of the precipitation in Northern Europe (Hawcroft et al., 2012), and extreme winds caused by powerful ETCs (also called as windstorms) are among the biggest natural hazards affecting Europe in terms of insured losses (e.g. Della-Marta et al., 2010; Schwerz et al., 2010) and forest damage (Gregow et al., 2017). Preparing for extreme winds is important for forestry, insurance companies and the offshore energy sector (Venäläinen et al., 2020), and predicting power outages caused by extreme winds is one of the key challenges for power grid operators (Tervo et al., 2019, 2020). Because ETCs form due to atmospheric baroclinicity, the strongest windstorms occur mainly in the winter season when the baroclinicity at mid-latitudes is greatest. However, the damage induced by the ETCs depends not only on the strength of the windstorms but also on the other bio-physical factors, such as the amount of frost in the ground or in the coastal regions whether the sea is frozen or not (e.g. Gregow, 2013).

In Finland, there have been several impactful ETCs during the current decade (Valta et al., 2019, Appendix Table A2 in this report). Recently, Storm Aapeli in January 2019 went down in history as the strongest windstorm in Finland with the highest observed 10-minute wind speed of  $32.5 \text{ ms}^{-1}$  and the wind gust of  $41.6 \text{ ms}^{-1}$  (Tollman et al., 2019). High-impact ETCs occur sometimes at short intervals if the large-scale weather pattern is favorable. Examples of this are Storms Tapani and Hannu on consecutive days in December 2011 and Storms Eino, Oskari and Seija within four weeks at the end of 2013.

There are several ways to measure the intensity of ETCs which makes the consistent comparison between different studies difficult. For example, the review paper by Mölter et al. (2016) on the projections of future storminess over the North Atlantic European region mentioned seven different metrics for storminess such as minimum sea level pressure, storm tracks, track density and wind speed. Also, Catto et al. (2019) highlighted in their review paper that because the intensities of ETCs are sensitive to the method and quantity used to define them, there is “little consensus” on how the intensity of ETCs might change in the future. Naturally, besides the ambiguities in defining the ETC intensity, the remaining uncertainties in the climate model simulations also decrease the scientific consensus on the future changes.

Due to climate change, the winters in Finland are becoming warmer and the period when temperature stays below freezing is becoming shorter (Lehtonen et al., 2019; Ruosteenoja et al., 2020). As the frozen soil anchors trees solidly to the ground, the forests can become more vulnerable for storm damage because the frost season is shortening (Gregow et al. 2011, Jokinen



et al., 2015). Therefore, even if the ETCs themselves would not become stronger in the future, their impact can be more damaging in the warmer climate.

In addition to the damaging ETCs which are mainly cold-season weather phenomena, strong wind speeds occur also in association with extreme convective weather (ECW) during the summer season. For example, during the summer 2010, four named convective storms (Asta, Veera, Lahja and Sylvi) caused considerable damage, losses of 8 million cubic meters of timber for Finnish forestry. This is higher volume of damage than has been caused by the consecutive cold season windstorms in Finland so far (Onnettomuustutkintakeskus, 2011). However, the future projections of ECW are uncertain because climate models cannot resolve convection explicitly due to their coarse resolution.

The purpose of this review is to bring together the most updated knowledge of strong winds and ETCs in Northern Europe during the past, present and future climate. We aim to respond to the following questions: How has the wind climate in Northern Europe varied over the past decades? Will the strong wind conditions change due to climate change in Northern Europe and neighbouring locations? If they will, where, when and how? To respond to these questions, a short literature review based on altogether 91 scientific articles and project reports has now been prepared. Of the summarized literature, some of the papers deal with strong winds in the past and current climate using reanalysis data and some of them reveal predicted changes in wind speeds using climate models. Examples given in the review consist for instance of comparisons between low and high spatial resolution predictions. Storm severity and impacts regarding past and current climate and also risks of future wind damages are also summarized on the basis of many scientific articles. Since ECW can also trigger strong winds, we summarize most up-to-date details regarding ECW impacts on wind in Northern Finland in both past and future climate.

This review is structured as follows. In every section, we present the knowledge regarding Northern Europe first and then give additional details about Finland. Section 2 presents results on the past climate and current conditions, and is divided into parts that present the observed occurrences of winds in general, ETCs, and winds induced by ECW. Regarding ETCs, we extend our analysis also for the North Atlantic region because a large number of studies focus mostly on the North Atlantic storminess. Section 3 deals with the projections of future climate and, furthermore, introduces briefly the risks regarding transitioning tropical cyclones. Finally, concluding remarks are given at the very end of the review.

## **2. Past and current climate**

### **2.1 Wind speeds**

#### **2.1.1 Trends in wind speeds based on observations**

Trends in the near-surface wind speeds in Northern Europe have been investigated using homogenized in-situ observations. They do not describe the intensity of storms but represent the

changes in general wind climate averaged over the years. With respect to the reviewed articles, the trends have been investigated over different time spans: Sweden 1953-2013 (Minola et al., 2016), Estonia 1970-1991 (Keevallik and Soomere, 2009) and Finland 1959-2015 (Laapas and Venäläinen, 2017). Unfortunately, any published papers about homogenized wind speed trends in Norway or Denmark were not found. In Sweden and Finland, the trends comprise varying numbers of measurement stations whereas the wind speed trend in Estonia includes only one site from Pakri, which is located in the northern coast of Estonia. Furthermore, both Laapas and Venäläinen (2017) and Minola et al. (2016) present wind speed trends also for a common 30-year time period of 1979-2008 for comparison purposes.

According to Minola et al. (2016), the values for the annual mean wind speeds in Sweden show a decrease of  $-0.06 \text{ ms}^{-1} \text{ decade}^{-1}$  for the period of 1953-2013. Similarly in Pakri, Estonia, a negative trend of  $-0.38 \text{ ms}^{-1} \text{ decade}^{-1}$  calculated over the whole year from the period 1970–1991 was reported in the review study by McVicar et al. (2012), which relies on the study by Keevallik and Soomere (2009). Consistently with the declining trends in Sweden and Estonia, wind speeds have shown a negative trend of  $-0.1 \text{ ms}^{-1} \text{ decade}^{-1}$  also in Southwest Germany in 1974-2013 (Kohler et al., 2018). However, all these trends have been calculated using different time periods and thus the direct comparison needs to be done with caution.

In Finland, the trends over 1959-2015 using 33 stations were found to be slightly negative, being  $-0.09 \text{ ms}^{-1} \text{ decade}^{-1}$  for the monthly average wind speed and  $-0.32 \text{ ms}^{-1} \text{ decade}^{-1}$  for the monthly maximum wind speed (Laapas and Venäläinen, 2017). This means that in Finland the strong winds have slowed faster than the mean winds. One explanation could be the increase in growth of forests and the amount of total growing stock (Supplementary Table S2 in Gregow et al., 2017) by 8 % over 1990's and similarly 8 % in 2000's in Finland. This may have modified the surrounding conditions of the measurement stations by increasing shelter over larger regions. Laapas and Venäläinen (2017) acknowledge this gap in their paper by saying that one potentially important and useful metadata that was lacking for wind speed homogenization was the information about possible changes in weather station surroundings, e.g. possible new buildings and changes in flora around the station.

During the time period of 1979-2008, the annual mean wind speeds have declined by  $-0.14 \text{ ms}^{-1} \text{ decade}^{-1}$  in Sweden and  $-0.17 \text{ ms}^{-1} \text{ decade}^{-1}$  in Finland (Table 1). In winter, the declining trends are smaller ( $-0.03 \text{ ms}^{-1} \text{ decade}^{-1}$  in Finland and  $-0.01 \text{ ms}^{-1} \text{ decade}^{-1}$  in Sweden), and in the case of Sweden, not statistically significant (Minola et al., 2016). In Finland, the statistical significance was not reported. The largest difference in seasonal wind speed trends between the countries has occurred in summer, when the trend in Finland is  $-0.21 \text{ ms}^{-1} \text{ decade}^{-1}$  while in Sweden it is only about half of it,  $-0.11 \text{ ms}^{-1} \text{ decade}^{-1}$ . Nevertheless, the values in Sweden and Finland are still surprisingly consistent with each other. In addition, the distinct decline in wind speeds during 1990's is visible in both countries (not shown), which increases the robustness of the result and implies that the feature is more likely caused by changes in atmospheric circulation and not by the flaw in the homogenization process (Laapas and Venäläinen, 2017).

**Table 1:** *Annual and seasonal mean wind speed trends in  $\text{ms}^{-1} \text{decade}^{-1}$  for the period 1978-2008 in Finland (Laapas and Venäläinen, 2017) and in Sweden (Minola et al., 2016).*

Period	Finland	Sweden
Annual	-0.17	-0.14
Winter (DJF)	-0.03	-0.01
Spring (MAM)	-0.20	-0.15
Summer (JJA)	-0.21	-0.11
Autumn (SON)	-0.19	-0.26

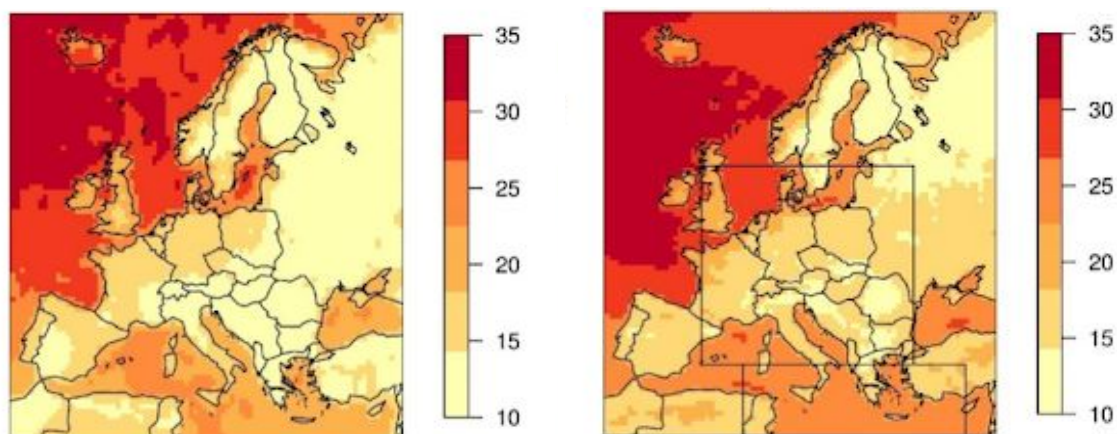
In addition, Laapas and Venäläinen (2017) found that the decreasing trend of mean winds is generally slightly stronger in western Finland than in eastern Finland (Figure 7 in Laapas and Venäläinen, 2017). The statistical significance of the trends was only calculated for each weather station separately and not for the annual wind speed trends over the whole Finland. Nevertheless, the wind speed trends in most of the weather stations were statistically significant. Similarly with the case in Finland, the spatial distribution of stations with most negative wind speed trends are located in southern and southwestern Sweden (Figure 5 in Minola et al., 2016).

While a number of studies have demonstrated that the recent decreasing trend in wind speeds is a global phenomenon (so called “global terrestrial stilling”, e.g. Vautard et al., 2010; McVicar et al., 2012), a very recent study indicates evidence of turning point to be occurred in 2010 and global wind speed recovery since then (Zeng et al., 2019). According to the study, the diagnosed reversal in the global terrestrial stilling can be linked to decadal variations in ocean-atmosphere climate indices, such as Tropical Northern Atlantic Index (TNA), North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO). The wind speed changing point in Europe was detected for 2003. Note that many stations from Finland and Northern Europe were missing from the analysis and thus, the conclusion of the study is not directly applicable to Northern Europe as such. In addition to terrestrial observations, there is evidence that global oceanic wind speeds have increased during recent decades, according to satellite observations (Zheng et al., 2016; Young and Ribal, 2019). However, these studies did not focus specifically on Northern Europe, and moreover, as Zheng et al. (2016) mention, the variation of oceanic wind speeds have noticeable regional and seasonal differences.

### 2.1.2 Wind speeds based on reanalyses

While the long-term wind speed observations in Northern Europe show a decreasing trend (Section 2.1.1), various reanalysis datasets give somewhat deviating results. The annual wind speeds in Northern Europe have a decreasing trend in ERA-Interim reanalysis from 1989-2008 whereas there are no trends in NCEP/NCAR reanalysis from 1979-2008 (Vautard et al., 2010) (see Appendix Table A1 for more information on the details of the reanalyses). Investigating seasons separately, Northern Europe has a decreasing wind speed trend in summer and autumn while there is an increase in spring and a small positive trend in winter based on ERA-Interim from 1980-2015 (Torralba et al., 2017). These results are somewhat similar in MERRA-2 reanalysis whereas JRA-55 shows much stronger and at some places opposite trends (Torralba et al., 2017). Furthermore, the annual near-surface wind speeds in the 110-year period of 1901-2010 in long-term reanalyses show contradicting trends over Northern Europe (Wohland et al., 2019). One explanation for the inconsistencies in wind speed trends between different reanalyses is the amount and quality of assimilated wind speeds due to evolving wind measurement techniques (Wohland et al., 2019). In addition, the chosen time period from which the trend is calculated has a significant effect on the magnitude and sign of the trend.

The extremeness in wind speeds in current climate can be estimated for example from the return levels. The 50-year return level for 10-m wind speeds is presented in Fig. 1 based on an ensemble of reanalyses (ERA-Interim, NCEP/NCAR and JRA-55) from 1980-2010 (left panel) and multi-model ensemble of EURO-CORDEX climate model simulations (Jacob et al., 2014) from 1979-2000 (right panel). Concerning the Nordic areas, the values between the reanalyses and the climate models differ relatively little on land and somewhat more over the sea. The spatial patterns in Northern Europe are similar to the 10-year return level of maximum wind speeds in ERA-Interim from 1979-2015 (Venäläinen et al., 2017). In Northern Europe, the likelihood for the highest wind speeds according to the models is the highest in the southern part of the Baltic Sea and near the Norwegian coast. Regarding Finland, the grid box average wind speed estimates for the return period of 50 years are below  $15 \text{ m s}^{-1}$ . However, as this value is only a spatial average of the grid box, the point-value of maximum wind gust could be considerably higher. Over the Baltic Sea, the corresponding wind speeds are around  $25 \text{ m s}^{-1}$  (for the spatial grid box averages) and would correspond to approximately 1.2 times as high wind gust speeds (indicating wind gust speeds on the order of  $30 \text{ m s}^{-1}$ ) for the grid box in concern.



**Fig. 1.** 50-year return level estimates for the instantaneous 10-m wind speed ( $\text{ms}^{-1}$ ) based on reanalysis datasets (left) and climate model output (right). The reanalysis-based estimates were derived from 6-hourly instantaneous wind speeds in 1980–2000 and are given as averages across three reanalysis datasets (ERA-Interim, NCEP1 and JRA-55). The climate model –based estimates were derived from daily maximum wind speeds 1970–2000 and are presented as multi-model means of 29 climate models. The boxes in the right panel are used in further analysis in the RAIN report. Modified from the FP7 RAIN project deliverable D2.5 (Groenemeier et al., 2016) and reprinted with permission from Nico Becker.

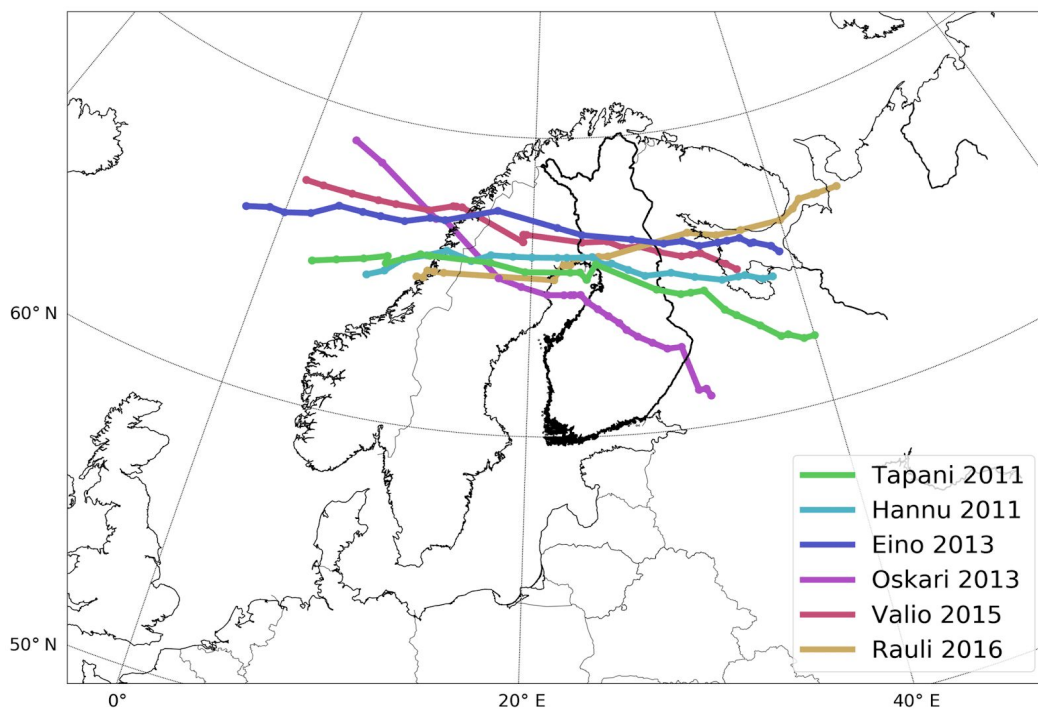
## 2.2 Extratropical cyclones

### 2.2.1 Extratropical cyclones based on reanalyses and in-situ observations

There is a growing number of literature investigating the observed trends and frequency of ETCs in the Northern Hemisphere. Out of these studies, some of them have expressed the trends and variability specifically in the Euro-Atlantic region. For example, the observed variability in cold-season ETCs in the Northern Hemisphere was assessed by Varino et al. (2018). They used the long-term ERA-20C reanalysis (Appendix Table A1) from the European Centre for Medium-Range Weather Forecasts (ECMWF) and tracked all ETCs with a vorticity-based algorithm. They found that the period of 1935–1980 is marked by a significant increase in Euro-Atlantic cyclone frequency, but the trend since the 1980's has leveled off. On the other hand, Befort et al. (2016) demonstrated that cyclone trends in the North Atlantic and Northern Europe in ERA-20C reanalysis disagree with another long-term reanalysis product, the NOAA 20th century reanalysis v2 (NOAA-20CR, Appendix Table A1). In particular, NOAA-20CR reanalysis shows an enhanced ETC activity around the 1920's, which is followed by a declining trend of events (in line with Wang et al., 2013). In contrast to NOAA-20CR, ERA-20C shows slightly increasing numbers of ETCs over the Euro-Atlantic region between 1920 and 1980. Therefore, Befort et al. (2016) stated that long-term trends of ETCs using ERA-20C and NOAA-20CR reanalyses should be interpreted carefully, especially before 1950.

Some studies (Krueger et al., 2013, 2014) have expressed that the long-term behavior of storm activity in NOAA-20CR should be interpreted with caution because the dataset may suffer from inhomogeneities. In particular, the time series derived from NOAA-20CR and from observations show opposing trends during the first half of the twentieth century, which challenges the increasing trend in storminess documented in Donat et al. (2011). Consistent with Krueger et al. (2013), Dangendorf et al. (2014) did not find any robust long-term trends in annual storminess using storm surge observations of the last 170 years over the Euro–Atlantic region.

As a summary, there seems to be very little consensus on the past long-term trends of storminess based on reanalysis products in the North Atlantic and Northern Europe. In the review paper by Feser et al. (2015), it was reported that “the proxy and measurement studies for the last decades and centuries generally show no storm trends” for the northeast Atlantic. It was also reported that for the Baltic sea, approximately equal number of studies show decrease, increase, and no trend at all.



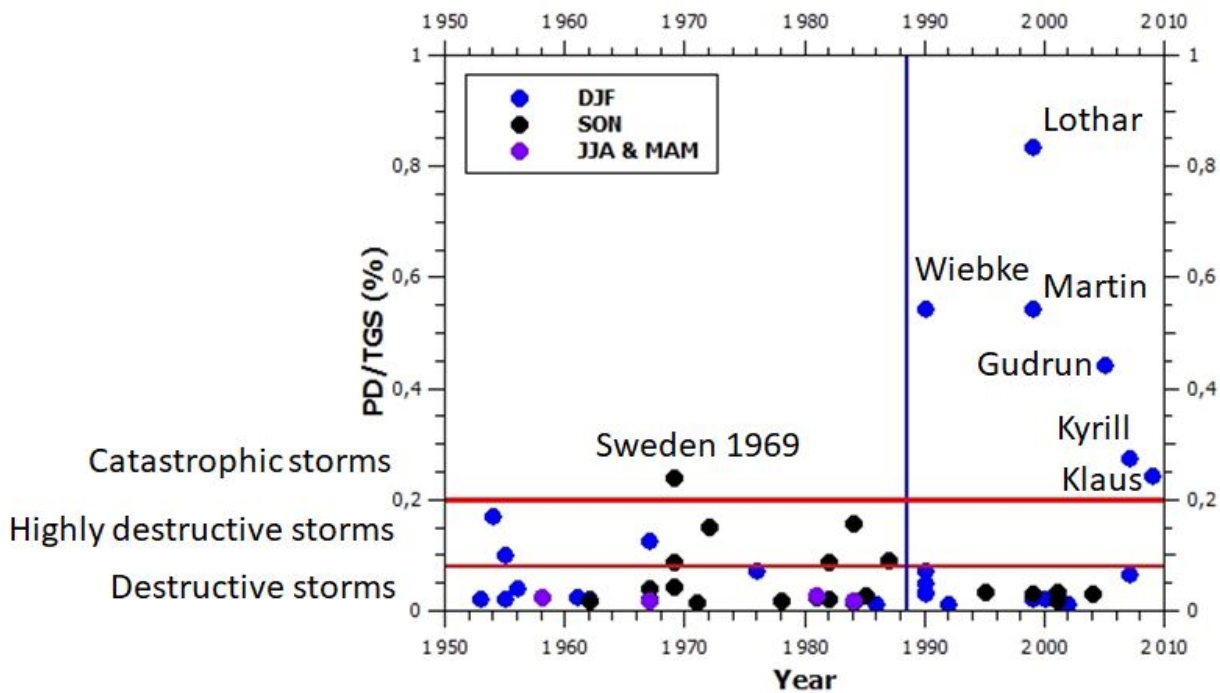
**Fig. 2.** Tracks of six strong ETCs affecting Finland in the 2010's. The tracks are based on the minimum of mean sea level pressure in ERA5 reanalysis. Figure adopted from Valta et al. (2019) and reprinted under Creative Commons Attribution 4.0 License.

The strong ETCs that have affected Finland have commonly occurred in November and December (Table A2) and they have traversed Finland typically at 63–65°N towards east or southeast as shown in Fig. 2. The strongest wind speeds in eastward moving ETCs typically take place on the equatorward side of their low centre, at the end of the feature known as the back-bent front (Schultz and Browning, 2017). Deepening ETC which travels across central Finland as shown in Fig. 2 pose thus high risk for wind damages especially for the southern half of Finland.

### 2.2.2 Extratropical cyclones based on observed impacts

In the past years, impact data has also been used to detect potential trends in windstorms. In Gregow et al. (2017), new evidence of a real change-point in the 1990's regarding an increase in windstorm intensities in Western, Central and Northern Europe was found. This result was obtained using primary forest damage reports (PD) of windstorm damage in the forests of Europe by combining this data with the total growing stock (TGS) statistics of picturing forest growth in Europe.

Using the validated set of windstorms (Fig. 3), Gregow et al. (2017) divided the storms into three categories: destructive storms, highly destructive storms, and catastrophic storms. It was found that the average intensity of the most destructive storms (indicated by  $PD/TGS > 0.08$  %) increased by more than a factor of three after 1990. However, most of the named storms in Fig. 3 have impacted western Europe, and thus the change-point detected in Gregow et al. (2017) needs to be considered with caution when talking about Northern Europe.



**Fig. 3.** Storm damage, as primary windstorm induced forest damage divided by total growing stock ( $PD/TGS$ ), is given separately for each season DJF (December-February), SON (September-November) and JJA & MAM (June, July, August, March, April, May). The well-known catastrophic storms of 1990-2010 have been indicated by name as well. The storms have been divided into three categories, separated by the red horizontal lines: destructive storms ( $PD/TGS < 0.08$  %), highly destructive storms ( $0.08\% \leq PD/TGS \leq 0.2\%$ ), and catastrophic storms ( $PD/TGS > 0.2\%$ ). Figure is a modification from Gregow et al. (2017).



What is different in Gregow et al. (2017) compared to research conducted using reanalyses (Donat et al., 2011; Wang et al., 2013; Roberts et al., 2014; Dawkins et al., 2016, Befort et al., 2016, Varino et al., 2018) or in-situ data (Hanna et al., 2008; Matulla et al., 2008; Vautard et al., 2010; Dangendorf et al., 2014; Stucki et al., 2014) is that a significant signal of increased storm damage was found using the non-meteorological data (strong wind-impact data). Additionally, by comparing the windstorm induced primary forest damage reports (Fig. 3) to the observed wind gust speeds reported in a storm catalogue<sup>1</sup>, it could be shown that the catastrophic forest damage has resulted from windstorms in which maximum wind gust speeds have varied between 50-60 ms<sup>-1</sup>. The return period of the catastrophic storms has been estimated to be between 100-200 years or more (Della-Marta et al., 2010). Most of the catastrophic windstorms have occurred in winter (December-February).

However, contrary to the findings of Gregow et al. (2017), there are studies which do not recognize increased windstorm damage in Europe over the past decades. For example, Barreiro (2010) reported that there is no upward trend in normalised windstorm losses in Europe in 1970–2008. Also Dawkins et al. (2016) showed that the 21st century is marked by a decline in damaging European windstorms which has led to a reduction in insured losses. However, these studies did not focus specifically on Northern Europe and Finland in their analyses.

In Finland, the observations show a decreasing trend in the number of storm days since the 1990's (Fig. 4). However, regarding the windstorm induced forest damage, there is no statistically significant trend in annual potential forest damage days in Finland during the period 1979-2013 (Jokinen et al., 2015). The decadal variation shows that 1980's and 2000's had the highest number of potential forest damage days whereas 1990's had the lowest number (Fig. 4).

The most significant windstorms in Finland have been listed in Appendix Table A2. One should remember that there are no clear, objective criteria for naming a storm in Finland and moreover, the criteria throughout the years may not have always been the same. Therefore, the number of named windstorms does not indicate any climatological trends in the frequency of windstorms. Currently, a windstorm will be named if it is expected to cause significant damage on the land areas and usually the naming is done only after the first reported impacts.

One example of an intense ETC in the 1980's was Storm Mauri which caused major forest damage and two fatalities in Northern Finland (Laurila et al., 2020). Valta et al. (2019) investigated nine large-scale windstorms in Finland which caused notable forest damage during the 2010's. They found that the volume of forest damage is approximately exponentially correlated with the maximum wind gust speed to the power of ten. This means that only a small increase in the wind gust speed can significantly increase the wind damage.

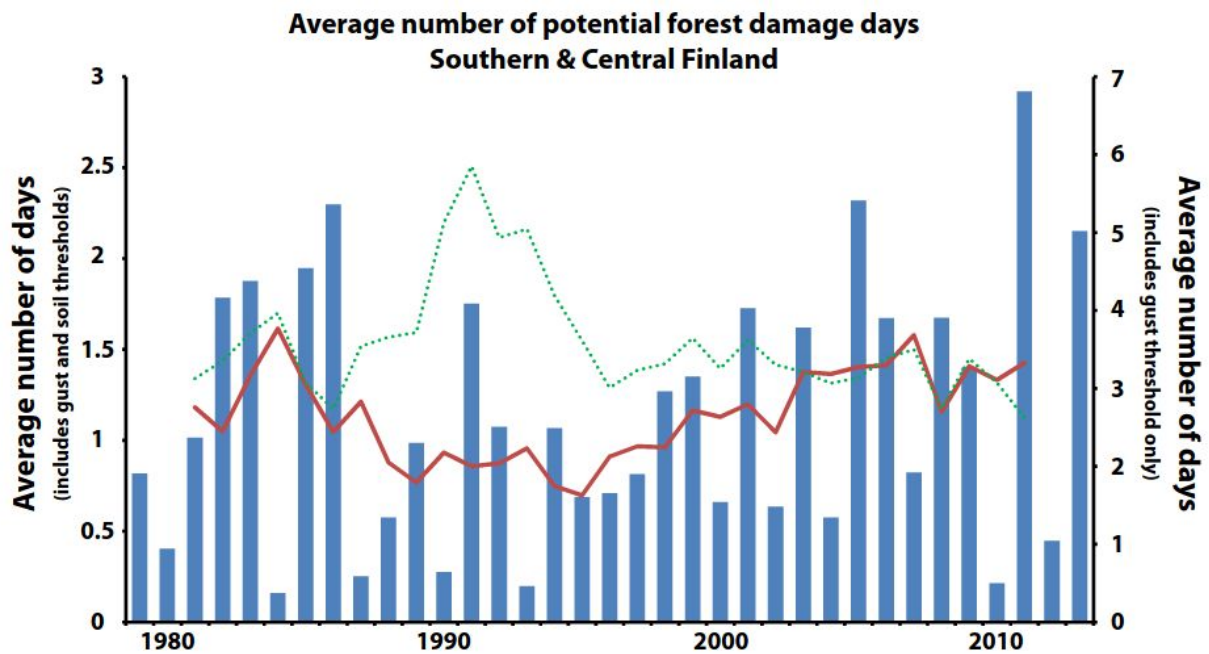
Forest damage is not the only impact that ETCs can cause in Northern Europe. ETCs are also able to cause storm surges which can lead to very damaging impacts for coastal infrastructure. According to Suursaar et al. (2018), the most serious meteorological and oceanographic as well as coastal impacts were connected to westerly approaching deep ETCs with

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<sup>1</sup> [www.europeanwindstorms.org](http://www.europeanwindstorms.org)



tracks crossing Scandinavia and Southern Finland. For example, the passage of Storm Gudrun in January 2005 through the Gulf of Finland towards the east-north-east caused record maximum sea levels in Helsinki (+151 cm) and Hamina (+197 cm) (Wolski and Wiśniewski, 2020). Wind and air pressure are actually the main factors affecting the short-term behaviour of sea level in the Baltic Sea (Johannson, 2014).



**Fig. 4.** Blue columns are the average number of potential forest damage days in Southern and Central Finland based on ERA-Interim when wind gust and soil thresholds are met or exceeded (see thresholds from Jokinen et al. (2015)). Vertical axis is on the left, and the red line is the 5-year running mean. The green dashed line is a 5-year running mean that uses the wind gust threshold only (vertical axis on the right). Figure adopted from Jokinen et al. (2015) and reprinted under Creative Commons Attribution 3.0 License.

It should be emphasised that the most hazardous ETCs are very rare and even a single windstorm may cause extensive damage. For example, Storm Gudrun in Sweden in 2005 destroyed 70 Mm<sup>3</sup> of forest (Bengtsson and Nilsson, 2007; Gregow, 2013). This is almost the same amount of forest damage than all other Swedish storms combined during the past 40 years. In addition, the amount of damage from ETCs is not necessarily only dependent on the meteorological factors; also for example the forest and infrastructure planning have an impact.

The economical impacts of ETCs can be very high. According to a leading reinsurance company, MunichRe, major winter windstorms in Europe can cause as much damage as a hurricane. For instance, the most expensive ETC in Europe's history remains Storm Lothar, which cost the insurance industry 8.6 billion euros<sup>2</sup>. In Finland, the report by Gregow et al. (2016) in the

<sup>2</sup> [www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards/winter-storms.html](http://www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards/winter-storms.html)

Finnish Government's analysis, assessment and research activities (Valtioneuvoston selvitys- ja tutkimustoiminta, VN TEAS) listed the economic losses of three severe ETCs: Storm Tapani in 2011, Storm Eino in 2013 and Storm Valio in 2015. According to the report, Tapani and Eino cost insurance companies 100 million and 30 million euros, respectively. The costs of Storm Valio were not known. Furthermore, in order to estimate the overall losses, one has to add the costs for electricity companies and landowners due to the damage in forests. These are typically in the order of tens of million euros in the case of strong ETCs. Unfortunately, in Finland, a systematic bookkeeping on the economic losses of different weather events, including ETCs, is still unsatisfactory, and even the existing information of economic losses are not shared. Therefore, in the report by Gregow et al. (2016), the authors call for a more open and comprehensive database of the economic losses caused by ETCs and other severe weather events.

### **2.3 Strong winds induced by extreme convective weather**

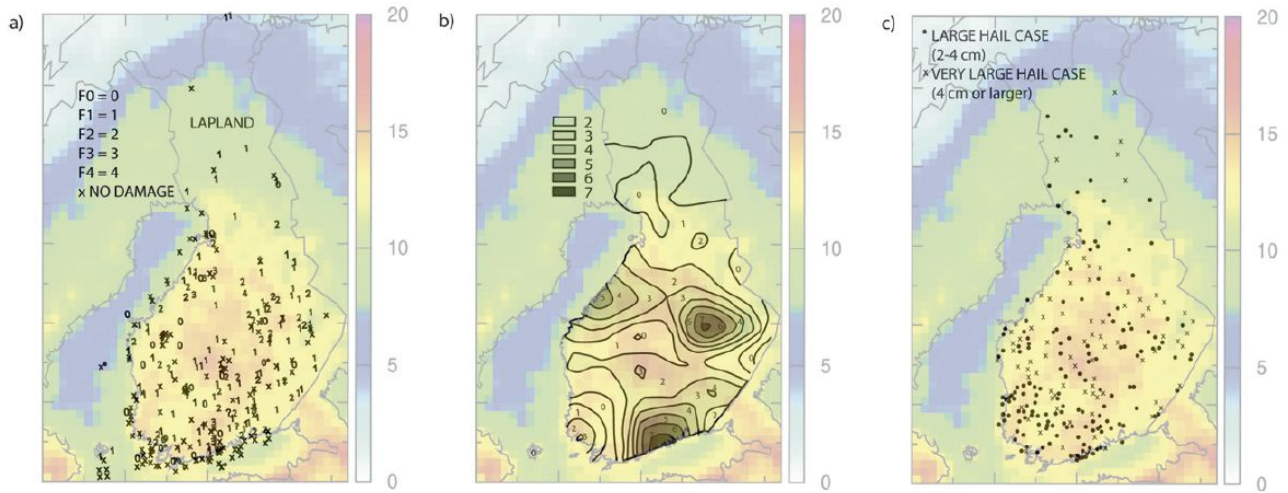
Extreme convective weather (ECW) phenomena are practically always related to thunderstorms and lightning. ECW contains the following phenomena: lightning, heavy precipitation, tornadoes, downbursts and large hails. Lightning, precipitation and wind gusts are always present in a thunderstorm while the occurrence of large hail or a tornado is a relatively rare case. From the above-mentioned phenomena, strong convective winds are related to downbursts and tornadoes.

Table A3 in the Appendix lists the most significant and strongest thunderstorms known to have occurred in Finland. In summer 2010, the four named thunderstorms (Asta, Veera, Lahja, and Sylvi) caused 8.1 M m<sup>3</sup> forest damage. Especially thunderstorm Asta caused extensive damage for forestry in Southeastern Finland due to the exceptionally strong wind gusts which resulted from the downbursts. In addition, thunderstorm Unto in July 2002 was the highest-latitude derecho that has ever been documented (Punkka et al, 2006).

Unfortunately, the occurrence and intensity distributions of tornadoes and downbursts in Finland are not well known. The main reason is that even the modern state-of-the-art observation systems cannot detect the occurrence of these phenomena and if they occur over an in-situ weather station the instrument is often damaged and no measurements regarding the maximum wind speeds are received. Therefore, the main source of information on downbursts and tornadoes are human observations on the incurred damage. Four examples of storms and their influences in Finland with great damage have been given by Pilli-Sihvola et al. (2016). It is important to note that the amount of impact data (reported damage) has grown substantially during the past decades but the primary reasons for this are societal changes (such as increased interest of citizens in severe weather) and technological advances (e.g. mobile technology).

Tornado climatology for Finland has been published by Rauhala et al. (2012). Their data series started already in 1930, and some observations are available before that as well. Their results (Fig. 5) indicate that the probabilities for the occurrence of a significant tornado in Finland

are largest in the central, southern and western parts of the country (Fig. 5b). Although it is likely that observations are missing, especially from the early decades, for the significant tornadoes the data set is considered to be relatively good (Rauhala et al., 2012).



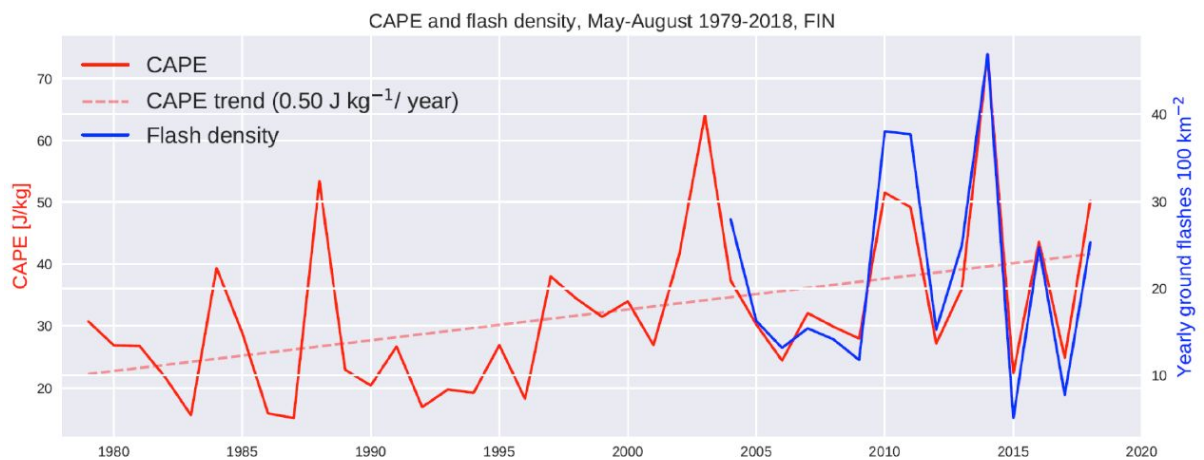
**Fig. 5.** Geographical distribution of (a) all tornado cases during 1796-2007 in Finland, plotted by the F scale as in the legend. (b) Annual probability (in percent) of at least one significant tornado in an 80 km x 80 km area based on the 1930-2007 statistics. (c) Geographical distribution of severe hail cases in Finland during 1930-2006 from Tuovinen et al. (2009). All figures are overlaid on the average annual number of thunderstorm days for Finland. Adopted from Rauhala et al. (2012). © American Meteorological Society. Used with permission.

The observational time series of downbursts are hardly complete: the only known study (Huttila et al., 2009) examined the occurrence of downbursts in a 100 x 100 km<sup>2</sup> area in southern Finland in 2002-2007. The occurrence of a downburst was assumed if a report of fallen trees (available in the Finnish Rescue Service database called Pronto) was collocated with observed lightning (available from the Finnish lightning location systems) within 2 hours of the Pronto-report. The probability of occurrence depends on the size (i.e., the area of influence) of the downburst. However, because exact statistics regarding the area of influence does not exist, Huttila et al. (2009) calculated the probabilities for two areas: 0.01 km<sup>2</sup> and 0.5 km<sup>2</sup>. The former represents downburst impact area of e.g. 100 m x 100 m (or 50 m x 200 m) while the latter e.g. 500 m x 1000 m area, respectively. Based on the method, Huttila et al. (2009) concluded that the annual point probability of occurrence of a downburst is about 0.002 (Table 2). The risk is the highest in July. The interpretation of the annual total probability for the larger area (i.e., 0.00175) is that a downburst that causes a rescue-service reported forest damage in some location occurs on average every  $1/0.00175 = 571$  years.

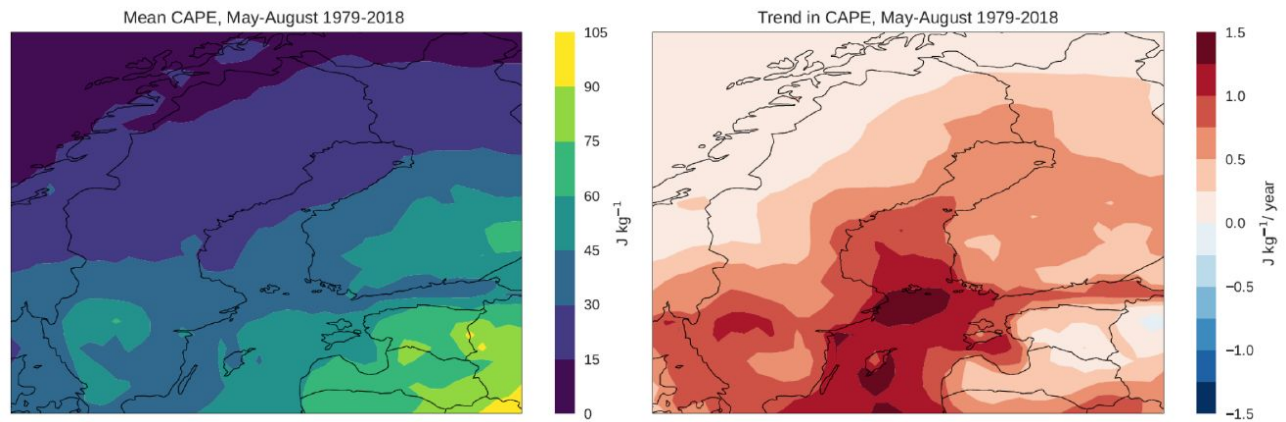
**Table 2:** The probability of occurrence of a downburst at ground based on two areas of influence (see text for details). Adopted from Huttila et al. (2009).

Month	Cases per year	Area of influence 0.01 km <sup>2</sup>	Area of influence 0.5 km <sup>2</sup>	Monthly/annual probability, 0.01 km <sup>2</sup>	Monthly/annual probability, 0.5 km <sup>2</sup>
5	0.3	0.003	0.167	$0.33 \cdot 10^{-6}$	$16.7 \cdot 10^{-6}$
6	3.0	0.030	1.500	$3 \cdot 10^{-6}$	$150 \cdot 10^{-6}$
7	21.7	0.217	10.833	$21.7 \cdot 10^{-6}$	$1083 \cdot 10^{-6}$
8	9.5	0.095	4.750	$9.5 \cdot 10^{-6}$	$475 \cdot 10^{-6}$
9	0.5	0.005	0.250	$0.5 \cdot 10^{-6}$	$25 \cdot 10^{-6}$
<b>Tot.</b>	<b>35.0</b>	<b>0.350</b>	<b>17.500</b>	<b><math>35 \cdot 10^{-6}</math></b>	<b><math>1750 \cdot 10^{-6}</math></b>

The risk of strong winds induced by ECW can be estimated also from environmental factors which typically lead to ECW. In Finland, Ukkonen and Mäkelä (2018) found significant positive seasonal trend in summertime convective available potential energy (CAPE) calculated from ERA5 reanalysis data and a good correlation of CAPE (averaged over the summers) with the annual amount of observed lightning (Figs. 6 and 7). However, CAPE over Finland features large interannual variability (Fig. 6) and thus, it is difficult to say whether the observed trend is driven by climate change or is it caused by decadal variability in the atmospheric circulation. Moreover, CAPE does not tell directly the occurrence of convective storms but rather acts as a proxy variable for convection-supporting environments.



**Fig. 6.** The time series of mean summertime CAPE (solid red line) and its linear trend (dotted red) over Finland from 1979 to 2018, derived from ERA5. Also shown is the flash density for cloud-to-ground flashes beginning from 2004 after which the performance of the lightning location system can be considered homogeneous in space and time. Adapted from Ukkonen and Mäkelä (2018).



**Fig. 7.** The mean summer CAPE in Northern Europe based on ERA5 in 1979-2018 (left) and its spatial trend (right). Adapted from Ukkonen and Mäkelä (2018).

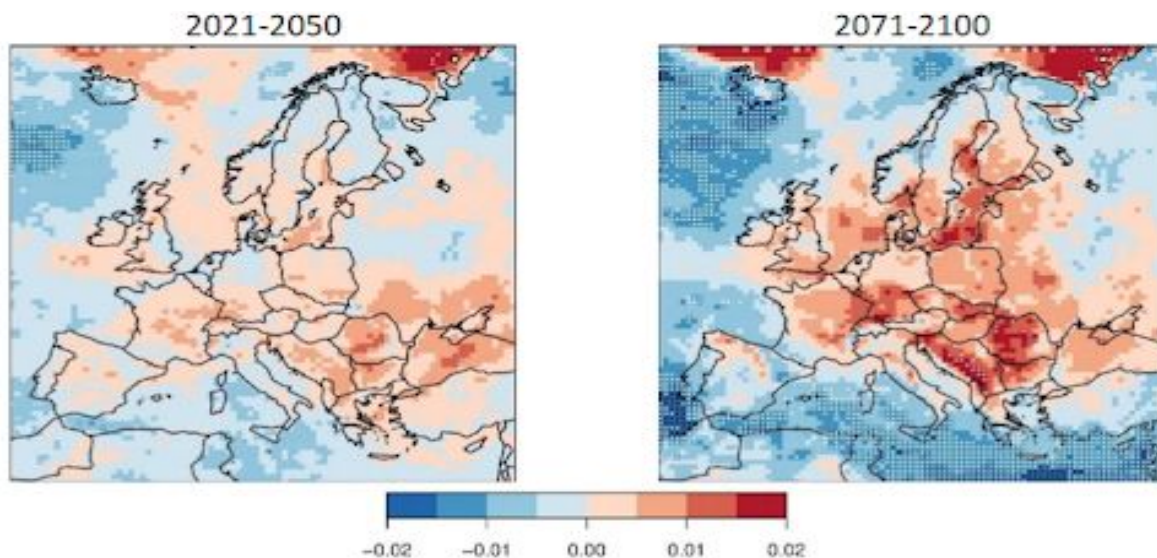
### 3. Future conditions

#### 3.1 Wind speeds

There are only a handful of studies which focus on the future changes in wind speeds specifically in Northern Europe. One of these studies is the paper by Pryor et al. (2012) in which the changes of wind speeds in Northern Europe under climate change scenarios were investigated. They relied only on a single model simulation, conducted by the ECHAM5 model under the Special Report on Emissions Scenarios (SRES, Nakicenovic et al., 2000) A1B emission scenario and dynamically downscaled using two regional climate models. The main result was that strong winds are not likely to evolve out of the historical envelope of variability until the end of the current century. Pryor et al. (2012) also emphasized the fact that internal climate variability will likely play a substantial role in strong winds throughout the current century.

In addition to Pryor et al. (2012), Gregow et al. (2012) investigated the changes in probabilities of extreme geostrophic wind speeds in Northern Europe until 2100. The geostrophic wind speeds were considered rather than the true surface wind speeds because the geostrophic wind speeds are less affected by model parametrization (e.g. Zilitinkevich et al., 2002). The analyses focused on the cold season from September to April. The extreme wind speeds were analysed using the Generalized Extreme Value (GEV) theory (e.g. Coles, 2001) and the block maxima approach. Calculations were conducted with six GCMs separately for the three scenarios A1B, A2, B2 and for a combined set of scenarios A1B:A2:B2 where the maximum annual values from each model during the September-April period were combined. Contrary to Pryor et al. (2012), a shift towards higher wind risk appeared stronger over the northeastern part of Europe. As regards the risk for strong wind conditions occurring once in 50-years, especially Northern Finland and northern part of Eastern Finland are in the risk zone (Gregow et al., 2012). However, the resolution used was very low and thus, the computations lacked detail that higher resolution models can give.





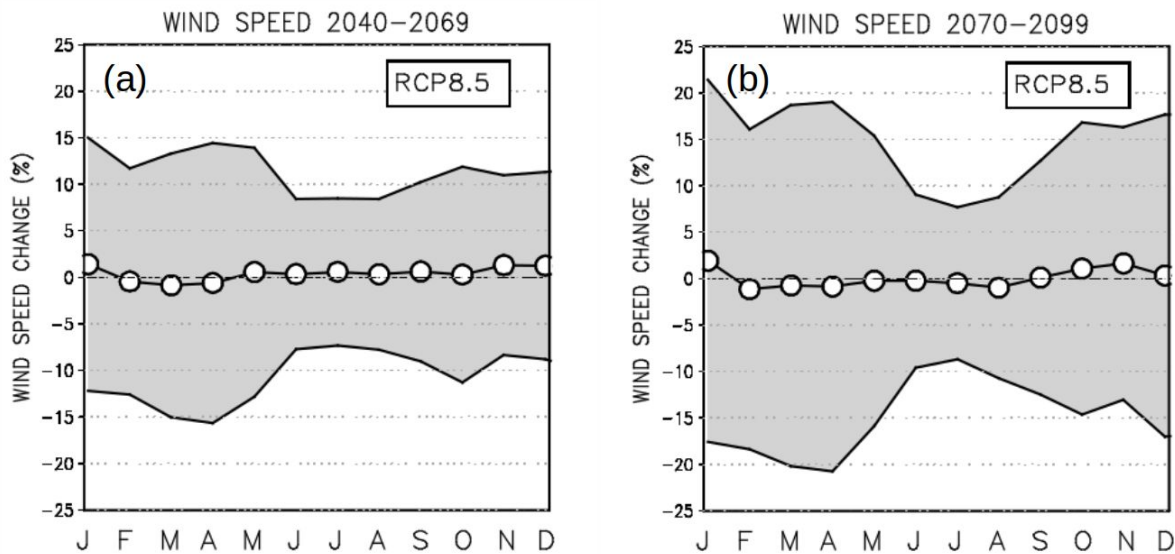
**Fig. 8.** *The change of annual exceedance probability of the 50-year return period of 10m wind speeds in Europe. The figures are based on 29 regional scale climate models and the RCP8.5 scenario (Groenemeier et al., 2016). Details of the significance of the results can be found in Groenemeier et al. (2016). Figure reprinted with the permission from Nico Becker.*

Groenemeier et al. (2016) used a multi-model ensemble of 29 EURO-CORDEX simulations and a higher resolution than Gregow et al. (2012), and the maximum daily wind speeds were examined instead of geostrophic wind speeds. Furthermore, Groenemeier et al. (2016) used the newer Representative Concentration Pathway (RCP) emission scenarios. Fig. 8 shows how the present-day 50-year return period in wind speed was projected to change by the mid-21st century (left) and by the end of 21st century (right) under the high-end RCP8.5 scenario. Surprisingly, the results are mostly contradictory compared to Gregow et al. (2012): according to Groenemeier et al. (2016), the wind speeds were projected to increase in south- and southwest part of Fennoscandia (Fig. 8), while Gregow et al. (2012) found the strongest signal in the Northeastern Finland (not shown). However, Gregow et al. (2012) calculated the changes only for the cold season, while Groenemeier et al. (2016) used annual scale.

Christensen et al. (2015) highlighted that the future conditions of wind speed in the Baltic Sea area are highly dependent on large-scale atmospheric circulation simulated by the climate models. According to them, the results diverge and thus it is not possible to estimate whether there will be a general increase or decrease of wind speeds in the future. On a local scale, many models indicate an increase of wind speeds over sea areas which are now ice-covered but not in the future. This feature was mentioned also by Räisänen (2017).

Similarly with Christensen et al. (2015), also Ruosteenoja et al. (2016) found very modest changes in wind speeds in Finland using Coupled Model Intercomparison Project 5 (CMIP5) models under the high-emission RCP8.5 scenarios. The multi-model mean change averaged over Finland in different months is mostly close to zero, with some slight signal for increasing wind speeds in the autumn and decreasing wind speeds in the spring (Fig. 9). The

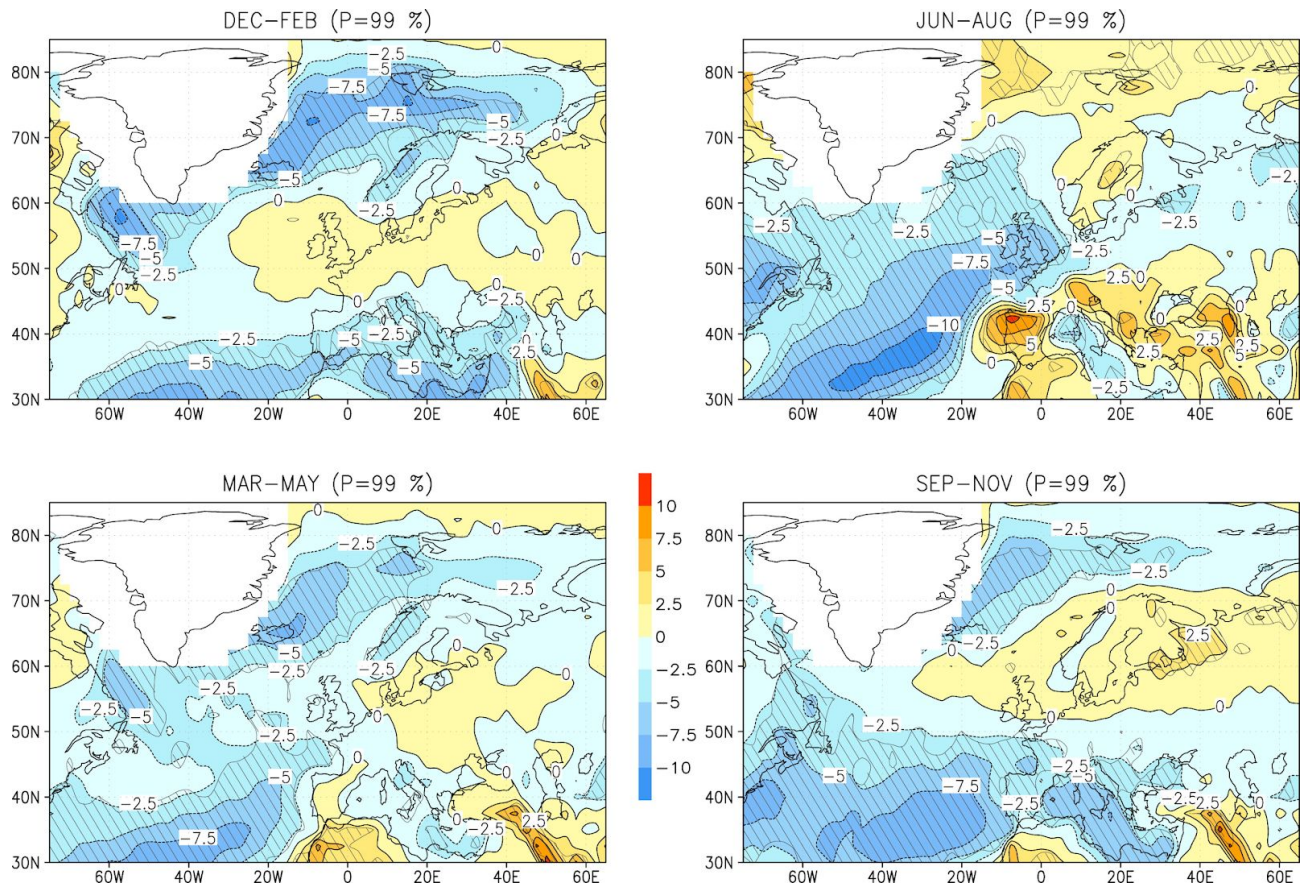
modest increase in the autumn is consistent with the results by Gregow et al. (2012). What is also noteworthy is the huge spread of the model results (see the grey shading in Fig. 9), which indicates large uncertainties, as noted also by Räisänen (2017). The spread in the wind speed changes originates from divergent changes in the atmospheric circulation between the different climate models. In general, the changes in atmospheric circulation is known to be a source of uncertainty in climate change projections (Shepherd, 2014).



**Fig. 9.** Projected changes in wind speed (in %) in Finland under the RCP8.5 scenario for the period 2040–2069 (a) and 2070–2099 (b), relative to 1981–2010. The multi-model mean projections for every calendar month (J = January, F = February, ...), based on simulations performed with 24–28 global climate models are denoted by open circles. Grey shading shows the 90 % uncertainty intervals for the change. Figure modified from Ruosteenoja et al. (2016) reprinted with permission from Geophysica.

A very recent study on future wind speeds in Northern Europe is published in the paper by Ruosteenoja et al. (2019). They investigated the geostrophic wind speeds for the seasons separately and used a set of 21 CMIP5 models and the high-emission RCP8.5 scenario. According to their results, and in line with Gregow et al. (2012) and Ruosteenoja et al. (2016), the high wind speeds in Finland are indicated to have a slight increase in autumn by the period of 2070–2099 (bottom right of Fig. 10). Ruosteenoja et al. (2019) also discovered that the frequency of strong westerly winds is projected to increase by up to 50 % in Northern Europe. Summer shows a slight increase of 99th percentile of wind speed over Norway, Sweden and the Gulf of Bothnia by the period of 2070–2099 while winter and spring depict decreasing changes over mostly Norway (Fig. 10). Although there is variation between models, the recent findings suggest that a slight increase in the high wind speeds in Finland in autumn is likely. Ruosteenoja et al. (2019) discovered also that the changes in the near-surface wind speeds in the climate models tend to be determined by

arbitrary changes in the surface properties rather than by changes in the actual atmospheric circulation, and thus, the near-surface wind speeds directly from the climate model output should be treated with caution.



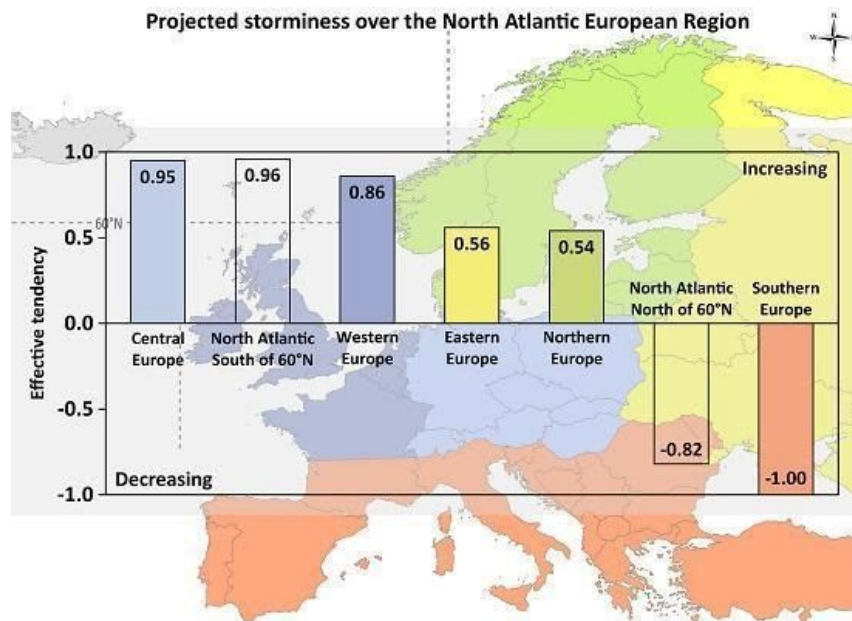
**Fig. 10.** Projected multimodel mean change (in %) in the 99th percentile of the geostrophic wind speed from 1971–2000 to 2070–99 under RCP8.5 in (top left) December–February, (bottom left) March–May, (top right) June–August, and (bottom right) September–November. The contour interval is 2.5%. Areas where more than 17 GCMs out of the 21 agree on the sign of change are hatched. Figure from Ruosteenoja et al., 2019, their Fig. 6. © American Meteorological Society. Used with permission.

Generally, the strongest winds tend to appear in the Northern Atlantic and near the coasts. The findings of Gregow et al. (2012) and Ruosteenoja et al. (2019) may thus, even with the low resolution, demonstrate the changes of the storm tracks in the future. That may give an indication of the area with pronounced risk for wind induced damage, such as forest damage, during the cold season (September–April). This risk is amplified by the fact that in the future, high and extreme winds occur in conditions which are warmer due to climate change. Then the soil is less often frozen (Gregow et al., 2011, Lehtonen et al., 2019) and more of the precipitation is likely to occur in liquid form (Räsänen, 2016).



### 3.2 Extratropical cyclones

As regards climate change impact on storminess on the European continent (Fig. 11), a coherent signal is found. Mölter et al. (2016) showed that there is a clear signal for increasing frequency and intensity of ETCs in Central and Western Europe, whereas in Eastern and Northern Europe the tendencies are not that certain. ETCs in Southern Europe are likely to decrease in the future. The original papers in the review article by Mölter et al. (2016) presented more diverse outcomes for Northern Europe than for the North Atlantic. In addition, the original papers in Mölter et al. (2016) were based mostly on the outdated CMIP3 models and the Special Report on Emissions Scenarios (SRES, Nakicenovic et al., 2000). Therefore, the results in those papers should be interpreted with caution, especially now in the era of CMIP6 model generation.

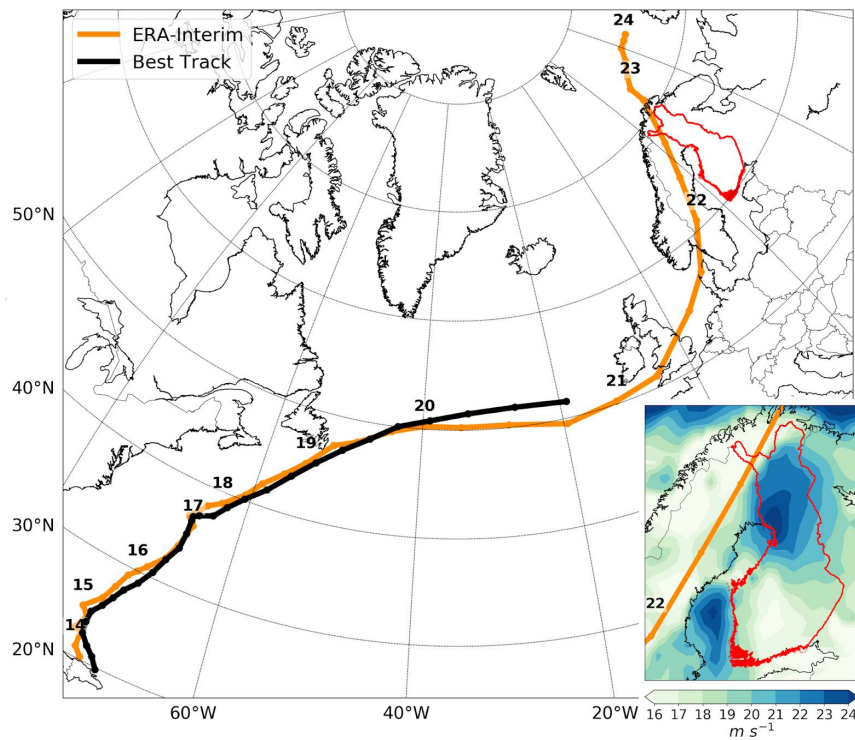


**Fig. 11.** *Effective tendencies of projected storminess over the North Atlantic European Region. Values are relative proportions of ratings indicating either increasing or decreasing tendencies in projected aspects of future storminess. Adapted from Mölter et al. (2016) and reprinted under Creative Commons CC BY 4.0 license.*

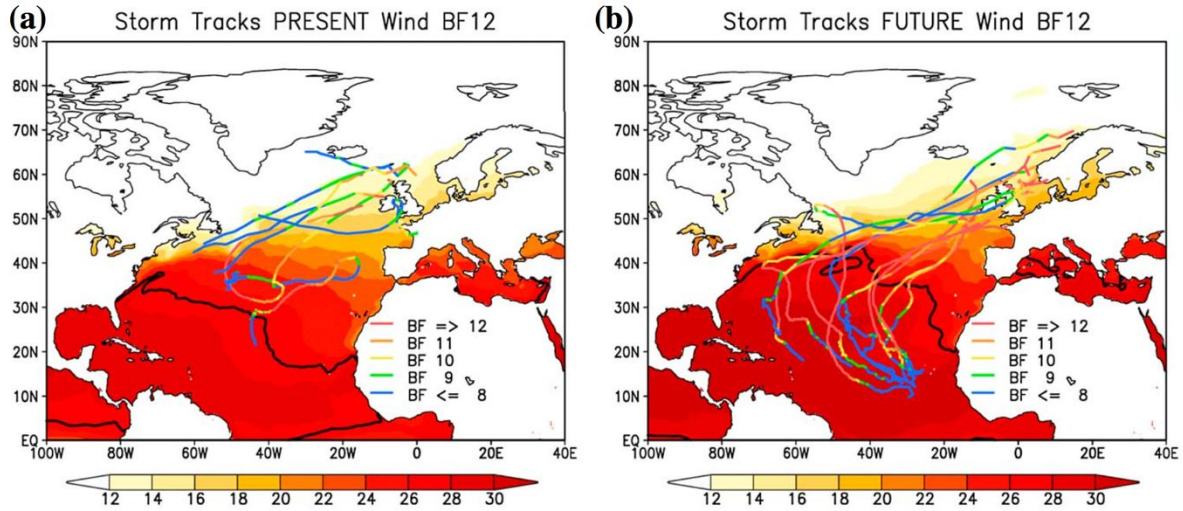
Catto et al. (2019) brought together the latest research on the future of windstorms in their review paper. According to the latest research presented in the review, models in CMIP5 project a reduction of 21 % in the top 5 % windstorms with associated extreme near-surface winds in the North Atlantic by the end of the 21st century using RCP8.5 scenario (Chang, 2018). However, the model agreement was relatively weak, indicating large uncertainties. Consistently, using the same scenario, Seiler and Zwiers (2016) reported a decrease of rapidly deepening ETCs in the North Atlantic by 17 % by the end of 21st century. Nevertheless, the direct comparison of studies by Chang (2018) and Seiler and Zwiers (2016) to studies in Mölter et al. (2016) is not straightforward because of the different domains used in the analyses. While Mölter et al. (2016)

indicated that the storminess is going to decrease in the area north of 60°N in the North Atlantic, Chang (2018) and Seiler and Zwiers (2016) obtained the same result for the whole North Atlantic.

ETCs which originate from tropical cyclones also have an impact in future storminess in Europe. Tropical cyclones in the North Atlantic (i.e. hurricanes) can travel to mid-latitudes, transition to ETCs and re-intensify to damaging windstorms while arriving in Europe (Hart and Evans, 2001). Usually they hit Western Europe, such as Storm Ophelia which hit Ireland in October 2017 (Rantanen et al., 2020), but some of the transitioning cyclones can reach even Finland and cause excessive damage, particularly for forestry (Fig. 12; Laurila et al., 2020). Due to global warming, the development region of hurricanes extends eastward and at the same time, sea surface temperatures are rising (Haarsma et al., 2013; Baatsen et al., 2015; Liu et al., 2017). These results indicate that hurricanes might more often reach mid-latitudes and re-intensify to hurricane-force winds along the Western Europe instead of dissipating. Therefore, Haarsma et al. (2013) state that there will be more extreme cyclones originating from hurricanes that reach Western Europe in the future (Fig. 13). Furthermore, very recent work by Michaelis and Lackmann (2019) suggests 1-2 more cyclones with tropical origins per year in the North Atlantic under RCP8.5-scenario by the end of the 21th century.



**Fig. 12.** Storm tracks of Hurricane Debby and Storm Mauri in September 1982 (black line from IBTrACS best track data set and orange line from ERA-Interim reanalysis). Dots are plotted every 6 h and the labeled numbers are days of September 1982 at 00 UTC. The inset figure shows maximum 10-m wind gusts between 21-24 September 1982 from ERA-Interim (colors,  $\text{m s}^{-1}$ ). Borders of Finland are colored red. Modified from Laurila et al. (2020). © American Meteorological Society. Used with permission.



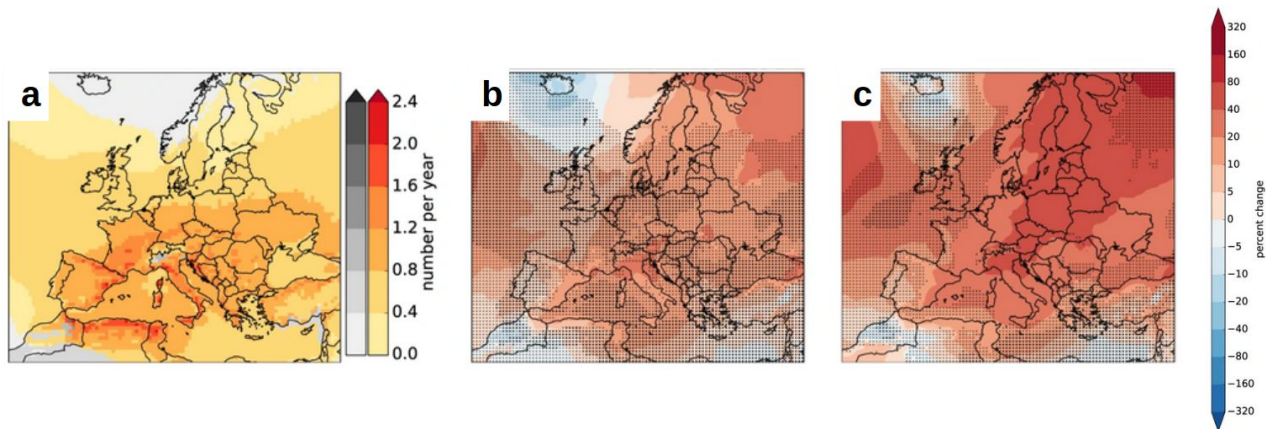
**Fig. 13.** Hurricane-force (Beaufort 12 >  $32.6 \text{ ms}^{-1}$ ) storm tracks during August-October in (a) present and (b) future climate. The colors of tracks indicate the storm intensity (Beaufort scale), background colors are sea surface temperatures in August-October ( $^{\circ}\text{C}$ ), and the black solid line denotes the  $27^{\circ}\text{C}$  isotherm. Adapted from Haarsma et al. (2013) and reprinted with permission from American Geophysical Union (AGU).

### 3.3 Strong winds induced by extreme convective weather

The estimations of changes in convective phenomena with climate change is challenging mostly because climate models are unable to resolve convection explicitly. In addition, extensive historical data is limited or non-existing. Based on preliminary assessments, the trend of higher temperatures seems to lead to convection-supporting changes in the storm environments in Europe via increased low-level humidity and thus increased instability (Púčík et al., 2017; Rädler et al., 2019). In the paper by Púčík et al., 2017, the authors did not find robust changes in severe weather environments in Northern Europe by the 2071–2100 period; the strongest increases in severe weather were instead projected consistently for South-Central, Central, and Eastern Europe.

Rädler et al. (2019) studied the future frequency of severe thunderstorms in Europe with a statistical model called AR-CHaMo (Rädler et al., 2018) and an ensemble of 14 regional climate models (Euro-Cordex, Jacob et al., 2014) using RCP4.5 and RCP8.5 scenarios. The signal is robust in RCP4.5 scenario in the southern part of Fennoscandia, including Southern Finland (Fig. 14b), but not robust in RCP8.5 scenario (Fig. 14b). The reason why the signal is not robust in a higher-emission scenario was not explained in the original article and therefore remained unclear for us. The projected magnitude of change in severe wind gusts associated with ECW is 5-20 % in RCP4.5 (Fig. 14b) and 20-40 % in RCP8.5 (Fig. 14c) by the end of the 21st century. While these numbers may sound large, however, it should be also emphasized that the occurrence of wind gusts  $\geq 25 \text{ ms}^{-1}$  due to ECW is very rare: in Finland on average only 0.0 ... 0.4 times per year (Fig.

14a). Therefore, even small changes in the absolute frequency lead to high relative changes in the areas where ECW is typically only occasional.



**Fig. 14.** Simulated annual 6-hourly periods with wind gusts  $\geq 25 \text{ ms}^{-1}$  in a) the historical period (1971–2000) and percentage of change at the end of the century (2071–2100) in the b) RCP4.5 and c) RCP8.5 scenarios. (Very) robust changes are indicated by (large) black dots. Trends in b, c are called (very) robust where the change is larger than (twice) the initial standard deviation of the model ensemble. In a), areas where models already diverge greatly for the historical period are displayed in gray. Modified from Rädler et al. (2019) and reprinted under Creative Commons CC BY 4.0 license.

#### 4. Concluding remarks

In this report, we reviewed the recent findings of past, current and future wind climate separately for wind speeds, extratropical cyclones and strong winds induced by extreme convective weather. The most important points of this review are summarised below.

For the past and current climate:

- The annual and seasonal wind speeds based on observations in 1959–2015 show a slight downward trend in Finland, consistently with the reports from Sweden (1951–2013) and Estonia (1971–1990).
- While multiple reanalyses show a decreasing wind speed trend in Northern Europe from 1979 onwards, not all trends are significant and also contradictory results exist although mostly from coarser resolution reanalyses. The chosen time period largely affects the calculated linear trend.
- Regarding the impacts and wind induced damage, the potential forest damage days in Finland do not show a significant trend, whereas in Europe, divergent results on the trends of windstorm damage have been achieved. A change point for windstorm induced catastrophic forest damage has been analysed to have occurred in 1990.

- Reanalysis data indicate a positive trend in the convection-supporting environments over Finland during the past decades. However, it is unclear how this reflects the trends in wind gusts associated with the deep convection.

For the future climate:

- Due to large uncertainties in the response of atmospheric circulation for anthropogenic climate change, there is very little consensus on how the windiness is expected to change in the future in Northern Europe. If anything, the wind speeds in the autumn may increase a bit, and they blow more often from the west.
- The projected slight increase of winds in autumn is likely related to the eastward extension of storm tracks. The total number of strong extratropical cyclones in the whole North Atlantic region is estimated to decrease.
- Extratropical cyclones which originate from tropical cyclones may also have an impact in future storminess in Europe.
- All in all, windstorm induced risk is increasing in the future, because high and extreme winds occur in conditions which are warmer due to climate change. Then the soil is less often frozen and more of the precipitation is likely to occur in liquid form, thus the soils may be wetter too.
- Climate model simulations indicate that the frequency of severe thunderstorms in Northern Europe is expected to increase by 5-40 % by the 21st century, which increases the risk of strong wind gusts in the summertime.

Many studies of future changes in extratropical cyclones (ETCs) concentrate on the North Atlantic and those results are also relevant for Northern Europe since ETCs typically travel from the North Atlantic to Europe. In the future, it is expected that the intensity of the strongest ETCs in the North Atlantic would decrease, especially in the northern part of the basin. There are some indications that in the Southern North Atlantic the ETCs would strengthen in the future, but the uncertainty in the climate models is very large especially in the North Atlantic. The biggest reason for the apparent decreasing trend is the larger warming in the Arctic region compared to elsewhere in the globe, which decreases the meridional temperature gradient and thus acts to reduce the potential energy available for ETCs.

Regarding Finland, the most recent findings suggest that a slight increase in the high westerly wind speeds in autumn in Finland is likely although there is variation between individual models. The climate change effects on ETCs in Finland are more uncertain. However, even if the intensity of ETCs in Finland remains the same, the impacts of windstorms will alter due to the ongoing change in environmental conditions (decrease in soil frost, increase in forest growth), urbanization, and increased dependence on electricity and communication networks.

In the future, the impact modelling of extreme winds for the needs of forestry and other domains of society should be improved. This would require the combining of meteorological



models and forest databases together in order to simulate the potential impacts of future ETCs and extreme convective weather. This is particularly important because in our warming climate, the winters are warming rapidly and thus the season of frost which keeps the trees better anchored to ground is shortening. One of the present challenges is that systematic databases of storm-caused forest damage in Finland are missing. Combining wind gust simulations from high-resolution numerical weather models and the spatial information on the vulnerability of trees could give promising results for the estimated forest damage. This requires cooperation between forest scientists and atmospheric scientists, and fortunately the work is already started in collaboration between Finnish Meteorological Institute, Finnish Forest Centre, Natural Resources Institute Finland and Ministry of Agriculture and Forestry.

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## Appendix

**Table A1.** *The main information of the reanalysis datasets mentioned in this report.*

Reanalysis (reference)	Horizontal resolution	Vertical levels	Time resolution	Time period
ERA5 (Hersbach et al., 2020)	~31 km	137 levels	1 h	1979-present (to be extended to 1950)
MERRA-2 (Molod et al., 2015)	~50 km	72 levels	1 h	1980-present
JRA-55 (Kobayashi et al., 2015)	~55 km	60 levels	6 h	1958-present
ERA-Interim (Dee et al., 2011)	~80 km	60 levels	6 h	1979-2019
NCEP/NCAR (Kalnay et al., 1996)	~210 km	28 levels	6 h	1948-present
ERA-20C (Poli et al., 2016)	~125 km	91 levels	3 h	1900-2010
NOAA-20C v2 (Compo et a., 2011)	~210 km	28 levels	6 h	1871-2012

**Table A2.** *The most significant windstorms in Finland. Note that the list does not contain all the named windstorms, but only the most notable ones. The list and its information may be incomplete, especially for the old cases.*

Date	Name	Forest damage [M m <sup>3</sup> ] (estimated by The Finnish Forest Centre)	Other information
1-2 Jan 2019	Aapeli	0.1	The strongest windstorm on record in Finland (Tollman et al., 2019)
26-27 Sep 2018	Kuisma		
22-23 Jun 2018	Pauliina		
27 Aug 2016	Rauli	0.06 - 0.15	200 000 households without electricity
8-9 Jun 2016	Salomo		
2 Oct 2015	Valio	0.5 - 1.5	
23 May 2015	Lyyli	0.14	
8 Feb 2014	Laina		
13 Dec 2013	Seija	1	
1 Dec 2013	Oskari	0.2 - 0.7	
17 Nov 2013	Eino	1.5	230 000 households without electricity
30 Nov 2012	Antti	0.3	
27 Dec 2011	Hannu	3.5 (in total by storms Hannu and Tapani)	In total 570 000 households without electricity (Kufeoglu and Lehtonen, 2014)
26 Dec 2011	Tapani		
10-11 Nov 2008	Martti		
22-23 Dec 2004	Rafael		
15-16 Nov 2001	Janika	7.3 (in total by storms Janika and Pyry)	
1 Nov 2001	Pyry		
31 Jan 1997	Alli		Damage to infrastructure and buildings (roofs blown away) in northern Finland, roads and railroads closed
23 Jan 1995	Visa		

26 Oct 1985	Manta	4	
22 Sep 1982	Mauri	3	Two fatalities. More information in Laurila et al., (2020).
16 Nov 1978	Aarno	2.5	
23 Dec 1975	<i>Unnamed</i>		These three unnamed storms were the strongest windstorms in Finland before Aapeli 2019.
15 Dec 1975	<i>Unnamed</i>		
25 Feb 1971	<i>Unnamed</i>		

**Table A3.** The most significant thunderstorms in Finland. The list and its information is incomplete, especially for the old cases.

Date	Name	Forest damage [M m <sup>3</sup> ] (estimated by The Finnish Forest Centre)	Other information
12 Aug 2017	Kiira	0.1	Measured wind gust 32.5 ms <sup>-1</sup>
31 Jul 2014	Helena	0.4	
8 Aug 2010	Sylvi	8.1 (in total by storms Asta, Veera, Lahja, and Sylvi)	
7 Aug 2010	Lahja		
4 Aug 2010	Veera		
30 Jul 2010	Asta		
5 Jul 2002	Unto	1	Classified as derecho (Punkka et al., 2006).
10-11 Aug 1985	Sanna	0.5 (rough estimate)	
8 Jul 1972	<i>Unnamed</i>	0.5 - 1 (rough estimate)	So called Puumala thunderstorm ("Puumalan myrsky")
1 Aug 1961	Maire	1	



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